OFF-GRID PHOTOVOLTAIC SYSTEM DESIGN PROJECT

by

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ABSTRACT

This project uses the BP SX 150S solar panel to charge a 12 V battery. This battery powers an AIMS 400 W Modified Sine Wave Inverter to provide 120 V RMS AC power to a load of up to 40 W. Inverter efficiency was measured at different load conditions. A control circuit was implemented to prevent overcharging or over-discharging of the battery, by disconnecting it from the panel or the load, respectively. The control circuit turn-on and cutoff voltages were measured versus battery voltage, and the on-resistance of the MOSFET switches was measured for various load currents. A table of panel inclinations was calculated for different times of year, and these calculations were verified experimentally. The battery voltage was measured with respect to state of charge, and this data was plotted against the manufacturer's stated performance. Finally, the battery round trip efficiency was calculated to ensure it was within the requirements of the design.

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ACKNOWLEDGEMENTS

I would like to thank the faculty in the EE department for their support through my years at Cal Poly. Specifically, thanks to Yvonne Lynch for doing all she does to ensure students get the classes they need. Thanks also to Dr. Taufik, Dr. Dale Dolan, Dr. Ahmad Nafisi, and Dr. Samuel Agbo for their help and guidance on this project and in the power curriculum in general. Most of all I would like to thank Dr. Ali Shaban for advising me in this project and patiently answering my questions in class or office hours. It has been a great asset and blessing to have access to such a wealth of knowledge in the electrical engineering faculty.

INTRODUCTION

Testing on this project was divided up into four subsystems: the panel, the battery, the inverter, and the charge control circuit. First, the solar panel's voltage-current characteristic curve was taken by varying the load on the panel, giving a smooth curve showing the voltage as current varies from no load to full load. This was done on two different sunny days to show a range of variance in insolation. The panel tilt was also calculated by month, based on time of the year and panel latitude. These angles were verified experimentally by varying the panel in 5 degree increments and measuring the open circuit voltage and short circuit current for each angle.

The charge control circuit was designed to disconnect the battery from the panel when the terminal voltage exceeds 14.5 V, and to disconnect it from the load when the terminal voltage drops below 12 V. This is done using a comparator to compare the battery voltage to two reference voltages of 14.5 V and 12 V. The comparator outputs control the gate signals of two MOSFET transistors connecting the battery to the panel and to the inverter (see System Circuit Diagram in Figure 3). The MOSFET gate signals were measured against the battery voltage to ensure the circuit was turning each MOSFET on at the correct voltage. The MOSFET drain source resistances were measured at various loading conditions to show these characteristics relate to each other.

The battery voltage versus state of charge was measured by discharging the battery at full load current from full charge until the terminal voltage dropped below 12 V. This 12 V threshold should occur at about 20 % charge, according to the manufacturer's datasheet. The voltage was measured at 3.3 amp-hour intervals. Since the battery capacity is nominally 33 Ah, each interval represents one-tenth of the total capacity. Once this was done, the battery was recharged to full capacity by the design maximum charging current. Battery round trip efficiency was calculated at full load by plotting the input and output power versus time and approximating the area under each curve to find the total energy used for maximum current charging and discharging cycles.

Testing on the inverter consisted of measuring the minimum and maximum input voltages. The maximum AC current was also measured. The inverter is designed to automatically shut off if the DC voltage or AC current vary outside of these limits. Finally, the efficiency of the inverter was measured with respect to load current. This was done by measuring both DC input voltage and current and AC output voltage and current to obtain the input and output power for different load currents.

BACKGROUND

Initially, this system was designed as a humanitarian project to be used in rural villages in Malawi. When I first spoke with Dr. Shaban about designing an off-grid photovoltaic system, he mentioned that another student was interested in using such a system to bring electricity to Malawian villages with no access to a power grid. She had been to Malawi on various other humanitarian projects, and when I talked to her, she was excited to hear that I was interested in bringing technology to these villages, and I was excited at the possibility of seeing my senior project help people in need. We devised the goals of providing lighting, radio, and the ability to charge cell phones and laptops, which she emphasized was a huge need, as many cell phone users must currently walk miles to neighboring villages to access generators to charge their phones.

Loading Considerations:

Research on the power consumption of each device, and estimation of how many hours' use each device would receive in a day generated Table 1, below.

Appliance (AC)	Rated Power (W)	Adjusted Power (W)	Hrs/day	# Used	Energy/day (Wh)	Peak DC Pwr (W)	Peak AC Pwr (W)
LED lights	12	13.33	6	8	640	106.7	96
Radio	25	27.78	18	1	500	27.8	25
Cell Phone Chargers	4	4.44	1	50	222	222.2	200
Laptop Charger	90	100.00	8	1	800	100.0	90

Table 1: Calculated Power and Energy for Malawi Design

This gives a possible 2.2 kWh used per day, with as much as 400 W being drawn at once.

This can drain up to 180 Ah from the battery bus per day, if using a 12 V battery bus voltage. LED or CFL lights were an important element in these original specifications, as they use about one-fifth the power of an equivalent incandescent bulb. It was determined that LED bulbs would be preferable as they last up to 30 times longer than CFL's. This would prevent the villagers from replacing burned out bulbs with locally available alternatives, such as 60 W incandescents, which would severely increase the electrical load and limit the allowable duration of use.

Another consideration for this design was the requirement of an inverter that could provide 50 Hz, 230 V AC power, rather than the US standard of 60 Hz, 120 V. It would also need to use the local standard electrical outlet, the BS 1363 (see Figure 1 below).

Figure 1: BS 1363 Outlet [5]

One inverter that meets these specifications is the AIMS 3000 W, Modified Sine Wave Inverter. It runs off of 12 V DC and has two 230 V RMS outlets. This inverter retails for $399 on the website theinverterstore.com.

Weather and Climate Considerations:

This project must be effective year round, so it must be sized for the months which receive the least sunlight per day. In Malawi, these months occur during the rainy season, from December to March. In these months, on average, only 5 hours of sunlight are received per day (see Figure 2 below). Additionally during these months, it is fairly common to see 3 days without sunshine, because of cloud cover. To allow for extended periods with no sunshine, the battery bus was initially sized to store enough energy to last for 6 days while maintaining the loading conditions discussed above. This would require a battery bus of four 200 Ah batteries in parallel. Internet research revealed that the cost of a single 12 V, 200 Ah battery ranges around $500, bringing the cost of the bus to $2000.

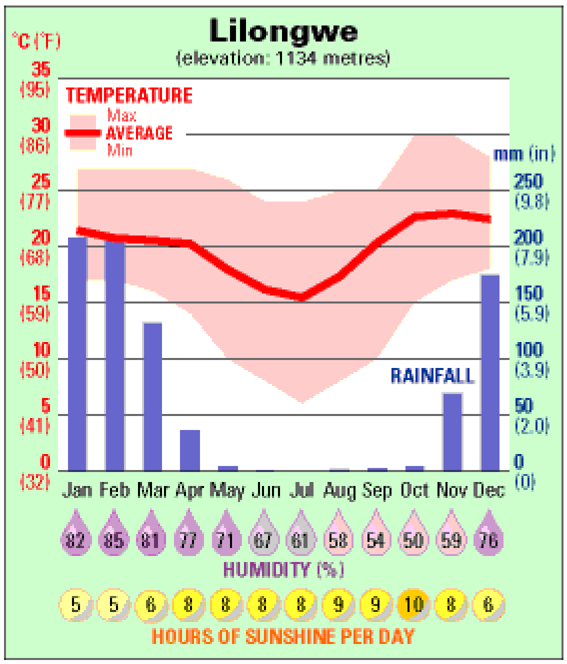

Figure 2: Climate Data for Lilongwe, Malawi

Including Peak Sun Hours [1]

Panel Considerations:

The total energy output from the array must be at least 2.86 kWh (accounting for both inverter efficiency and battery round trip efficiency of 0.9 and 0.8, respectively). The array must be able to provide this energy even in the months of the rainy season. During this season, the average amount of sunshine per day is about 5 hours. Using the equation

$$\mathbf{E_{array} = P_{panel}*n*t}$$

the number of panels, n, can be found, where t is the number of sunlight hours per day (5 for rainy season), and P_{panel} = 200 W. Solving for n, this equation gives about 2.86, which is rounded up to 3. One panel that meets these specifications is the Evergreen ES-A-200-FA3, a 200 W, 12 V panel retailing for $635 each. [3] Another is the Lotos 200 W, 12 V Solar Panel Battery Charger, available for $600. [4] The total cost for the full array of 3 panels would be $1800. This puts the total cost of panels, batteries, and inverter at $4200.

The optimal inclination of these panels to the north or south was calculated by month, with negative numbers indicating southern tilt (see Table 2 below). The panel tilt from horizontal matches the Sun's zenith angle (given in degrees).

Month	Day of Year	Declination	Zenith
Jan	15	-21.10	-7.10
Feb	46	-12.95	1.05
Mar	75	-2.02	11.98
Apr	106	10.15	24.15
May	136	19.26	33.26
Jun	167	23.39	37.39
Jul	197	21.18	35.18
Aug	228	13.12	27.12
Sep	259	1.41	15.41
Oct	289	-10.33	3.67
Nov	320	-19.60	-5.60
Dec	350	-23.40	-9.40

Table 2: Optimum Panel Inclination Angles in Lilongwe, Malawi by Month

Ultimately, the cost of components for this proposed project was too high. Also, none of my prospective partners were ready to start their senior project yet, and $4200 was a lot for one person to raise, so the load requirements were scaled back, and the system was redesigned for use in San Luis Obispo. Scaling down the load allowed for the use of a single panel and a single battery, as well as a smaller inverter using the American AC voltage standard of 60 Hz, 120 V, RMS. The panel used in the final project was borrowed from the Cal Poly EE Department. All measurements and calculations given hereafter reference the system after redesign and testing.

REQUIREMENTS

Total System Requirements:

The goal of the whole system is to supply 60 Hz, 120 V RMS AC power. It must receive this power from a solar panel and store it in a battery, and it must be able to support a 40 W load, according to the loading data given in Table 3, below. The numbers given under the "Adjusted Power" column take the inverter efficiency of 90% into account. These requirements must be met in San Luis Obispo, California, regardless of month of the year.

Appliance (AC)	Rated Power (W)	Adjusted Power (W)	Hrs/day	# Used	Energy/day (Wh)	Peak DC Pwr (W)	Peak AC Pwr (W)
LED lights	12	13.33	5	2	133	26.7	24
Radio	25	27.78	4	0	0	0.0	0
Cell Phone Chargers	4	4.44	1	4	18	17.8	16
Laptop Charger	90	100.00	8	0	0	0.0	0

Table 3: Calculated Power and Energy of Load

Panel Requirements:

The total daily energy demand on the battery is 151 Watt –hours (Wh) (See Sizing Worksheet, Appendix C). Accounting for a battery round trip efficiency of 80%, the panel must produce at least 190 Wh per day, operating between 12 and 15 V to match the battery voltage. It must be able to meet these requirements year round. To help in this goal, the panel inclination should be adjusted monthly to ensure that the inclination angle matches the Sun's zenith angle. This is most important in winter months, when the days are the shortest, and daily insolation in at a minimum.

Battery Requirements:

Loading and Sizing Calculations:

The battery used in this project must have a nominal voltage of 12 V. The total energy demand on the battery is a maximum of 151 Wh per day, with a peak load of 40 W. Dividing 151 Wh by 12 V gives a daily discharge of 12.6 Amp-hours (Ah). The battery must be able to power the load for two days without recharging while remaining above 20% charge capacity. To accomplish this, the battery must have a minimum capacity of 31.5 Ah, it must be allowed to discharge to 20% charge capacity, and it must have a round trip efficiency of 80%.

Weather and Climate Considerations:

The system must support the rated load for 2 days, after which the battery must be allowed to recharge. This reduction in days of storage (from 6 days in the Malawi calculations) was allowed because there is more sunlight in San Luis Obispo during the rainiest season of the year (winter to spring), and reducing the battery bus capacity from 200 Ah to 33 Ah decreased the battery bus cost from $2000 to about $100. See climate data in Table 4 below.

Though Table 4 only accounts for rainy days, and not for cloudy days, this information helps to give a general idea of sunny versus rainy days that occur throughout the year. Though it is impossible to ascertain that there will never be more than 2 consecutive days of rain or cloud cover, allowing for two days of use without recharging should let the battery charge last through most periods of cloud cover.

Climate Data for San Luis Obispo													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Rainfall **inches (mm)**	5.28 (134.1)	5.41 (137.4)	4.48 (113.8)	1.31 (33.3)	0.47 (11.9)	0.09 (2.3)	0.03 (0.8)	0.08 (2)	0.44 (11.2)	0.99 (25.1)	2.17 (55.1)	3.61 (91.7)	24.36 (618.7)
Avg. rainy days	9.0	8.5	9.1	4.5	2.3	0.6	0.5	0.4	1.4	2.8	5.2	5.9	50.2

Table 4: Climate Data for San Luis Obispo [2]

The battery must supply at least its nominal voltage of 12 V, but should not exceed 15 V. It must do this for all currents between no load and full load conditions (up to 3.3 A). It must have at least a 31.5 total Ah capacity.

Charge Control Circuit Requirements:

The charge controller must detect when the battery voltage drops below 12 V and disconnect it from the load. It must also detect when the battery voltage exceeds 14.5 V and disconnect it from the panel. This will lengthen the life of the battery by preventing overcharging or over-discharging.

Inverter Requirements:

The inverter used in this project must be able to provide an AC voltage of 60 Hz, 120 V RMS to a 40 W load, with an allowed input voltage ranging at least from 12 V to 15 V DC with

90% efficiency. The efficiency is important because an inefficient inverter draws significantly more power from the battery than is used by the load, so this would limit the length of usage time without recharging.

DESIGN

Total System Design:

This project shall consist of four component subsystems including the solar panel, the battery, the charge controller, and the inverter. See Figure 3 for a diagram of the assembled components.

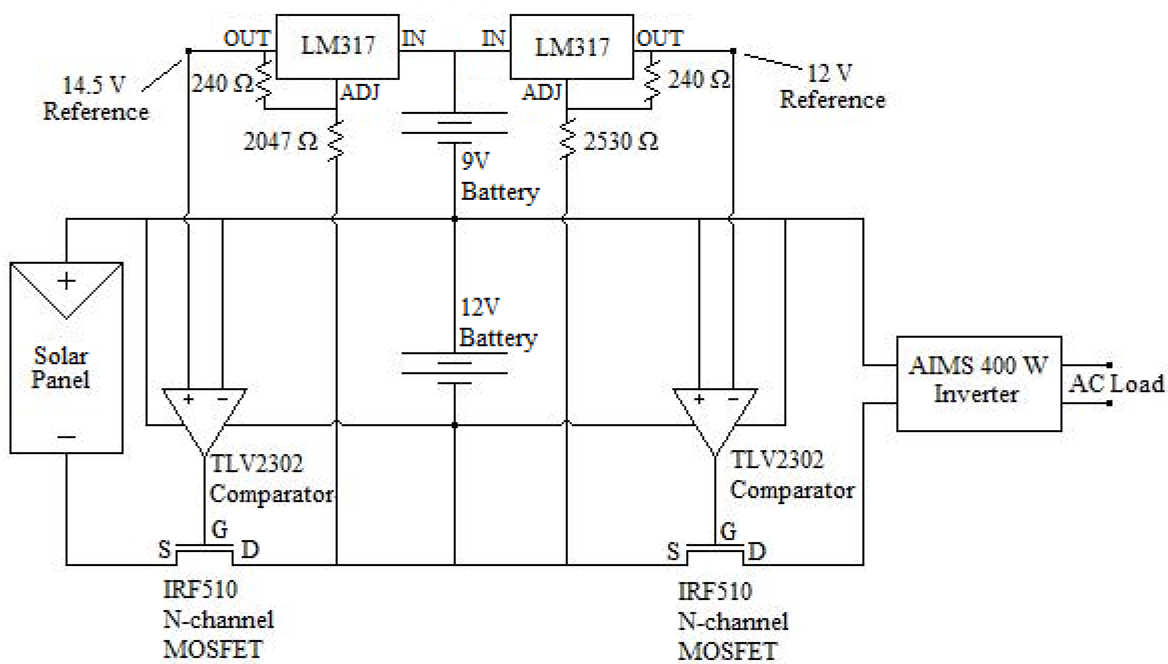

Figure 3: Off-Grid Photovoltaic System Circuit Diagram

Panel:

Panel Sizing:

Selection of a sufficiently sized panel is crucial, to ensure that it generates enough energy to replace that used by the load or lost to inefficiency. To aid in these calculations, peak sunlight hours are determined, and are defined as the number of hours of peak insolation (such as, at solar noon) that would produce the same amount of energy as the variable insolation dispersed throughout an entire day. According to weather data taken from www.gaisma.com (Table 5 below), in San Luis Obispo, the period from November to January has the minimum of peak sunlight hours, averaging about 5 peak sunlight hours per day. This means that a solar panel can collect an equal amount of energy in 5 hours of peak sunlight as it could throughout the day with varying sunlight.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Insolation, kWh/m²/day	2.63	3.40	4.70	6.08	6.95	7.23	6.79	6.13	5.03	3.89	2.90	2.38
Clearness, 0 - 1	0.53	0.53	0.57	0.61	0.63	0.63	0.61	0.59	0.57	0.55	0.54	0.52
Peak Sunlight Hrs/Day	5	6	7	8	9	9	9	8	7	6	5	5

Table 5: Climate Data for San Luis Obispo [2]

To meet the requirement of 189 Wh collected per day (Appendix C), the system must be designed for minimum insolation months (in this case, November through January). The following equation gives the relationship needed to calculate necessary panel output power.

$$P_{panel} * PSH = \text{Daily Energy}$$

P_{panel} is the nominal panel output, PSH is the peak sun hours for the design month (in this case, 5 hours), and Daily Energy is the required 189 Wh. Solving for P_{panel}, a 38 W panel is needed.

In this project, the BP SX 150S solar panel was used. It has a nominal power output of 150 W, almost four times the requirement of 38 W. This allows for some variance in output due to varying cloud cover, and also due to the fact that the panel may not operate at the maximum power point on its I-V characteristic curve. Table 6 below shows the panel's nominal characteristics.

	Voc (V)	Isc (A)	Vmp (V)	Imp (A)	Pmax (W)	Fill Factor
Nominal	43.50	4.75	34.50	4.35	150.08	0.73

Table 6: Nominal BP SX 150S Solar Panel Characteristics

<u>Panel Inclination:</u>

To help the panel maximize its output, the inclination can be adjusted monthly to match the Sun's zenith angle. To find the zenith angle, the latitude and the daily declination angle must be known. Zenith angle is calculated according to the following equation,

Zenith Angle = Declination Angle - Latitude

where negative angles correspond to southern latitudes and south tilting panels. The latitude for San Luis Obispo is 35 degrees N. The equation for determining the declination angle is as follows:

Declination Angle = 23.45 * sin[(360/365)*(n-80)]

where the variable n is the day of the year, beginning with n=1 on January first.

Below (Table 7) is the table of inclination angles calculated by month for San Luis Obispo. This is similar to Table 2 above except that for Malawi, a latitude of -14 degrees was used, and here a latitude of 35 degrees was used.

Month	Day of Year	Declination	Zenith
Jan	15	-21.10	-56.1
Feb	46	-12.95	-47.95
Mar	75	-2.02	-37.02
Apr	106	10.15	-24.85
May	136	19.26	-15.74
Jun	167	23.39	-11.61
Jul	197	21.18	-13.82
Aug	228	13.12	-21.88
Sep	259	1.41	-33.59
Oct	289	-10.33	-45.33
Nov	320	-19.60	-54.6
Dec	350	-23.40	-58.4

Table 7: Optimum Panel Inclination Angles in San Luis Obispo by Month

A zenith angle of -56.1 degrees means that the panel should be tilted 56.1 degrees due South. This data matches the data shown in Figure 4, below, which shows the Sun's elevation and hour angle by date and time. The tangential axis measures the Sun's hour angle throughout the day, measured from North, and the radial axis measures the elevation angle above the horizon. Note that the orange line represents the Sun's location on February 3, 2011, when this graph was obtained. The zenith angle is defined as the Sun's elevation angle above the horizon when its hour angle is 180 degrees, due South. The zenith angle in Figure 4 is approximately 47 degrees above horizontal, closely matching the zenith angle of -47.95 degrees (47.95 degrees South), predicted for February in Table 7 above.

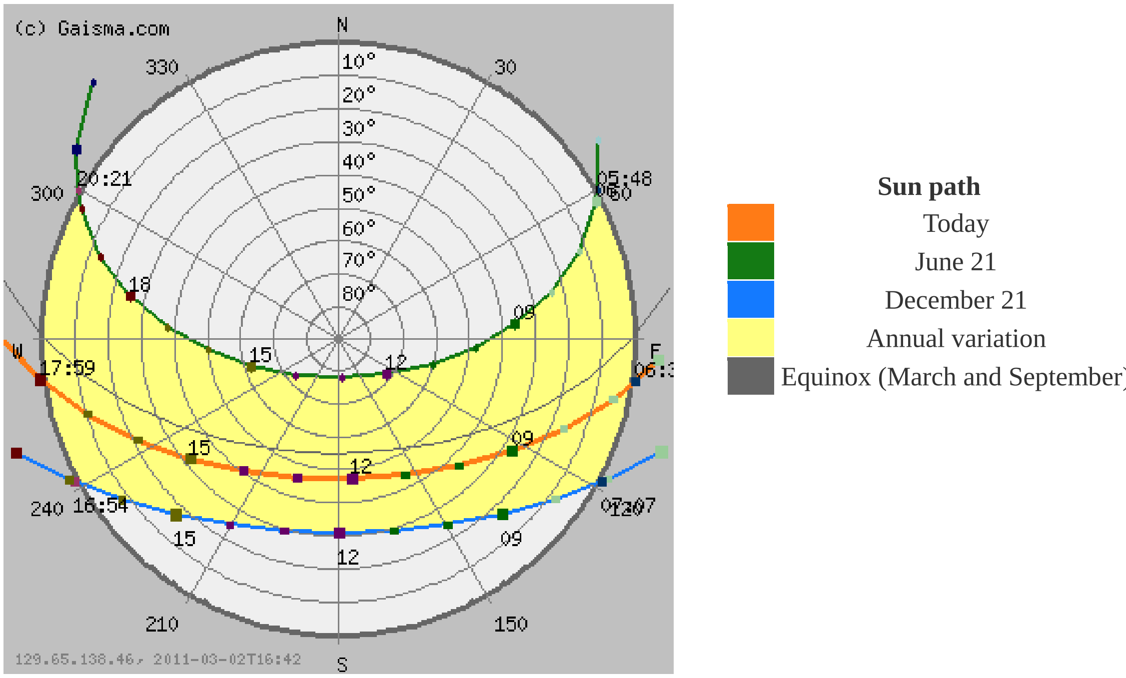

Figure 4: Solar Elevation Angle and Hour Angle

by Date and Time in San Luis Obispo (February 3) [2]

Battery:

For this project, a 12 V battery was used because the AIMS 400 W Inverter requires a 12 V input. The battery selected for this project is the Werker WKDC12-33PUS, which has a 33 Ah rated capacity. This meets the minimum necessary capacity requirement of 31.5 Ah. When charging, it must be charged up to 14.5 V. When fully charged and disconnected from the charging source, its nominal terminal voltage is 12.8 V. To protect the battery’s lifespan, it should not be discharged to below 20% of its rated capacity. The nominal battery voltage at 20%

capacity is 12 V. This means that the battery should not be discharged below 12 V. Figure 5, below, shows information provided by the manufacturer regarding how depth of discharge affects number of charges in the battery's life. Note that 80% discharge means the battery is discharged to 20% capacity, the maximum discharge allowed by this design. Figure 6 shows the nominal voltage plotted against remaining charge capacity, as specified by the manufacturer.

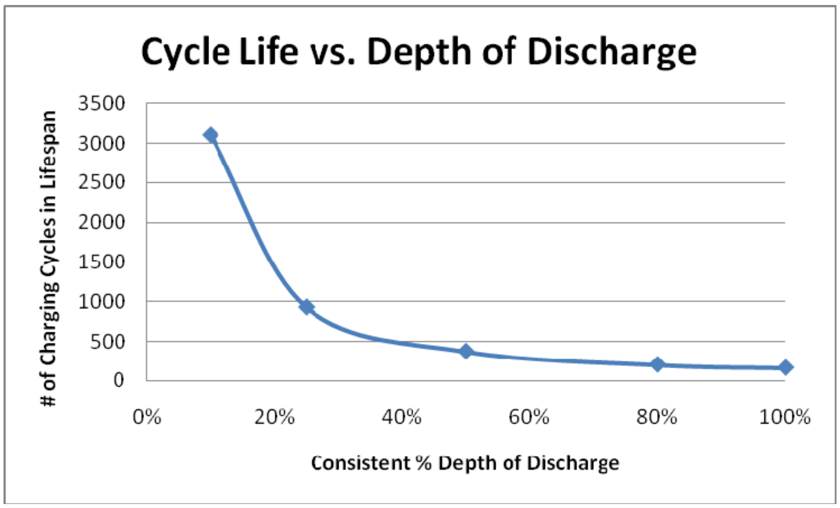

Figure 5: Charging Cycles in Battery Lifespan vs. Depth of Discharge [7]

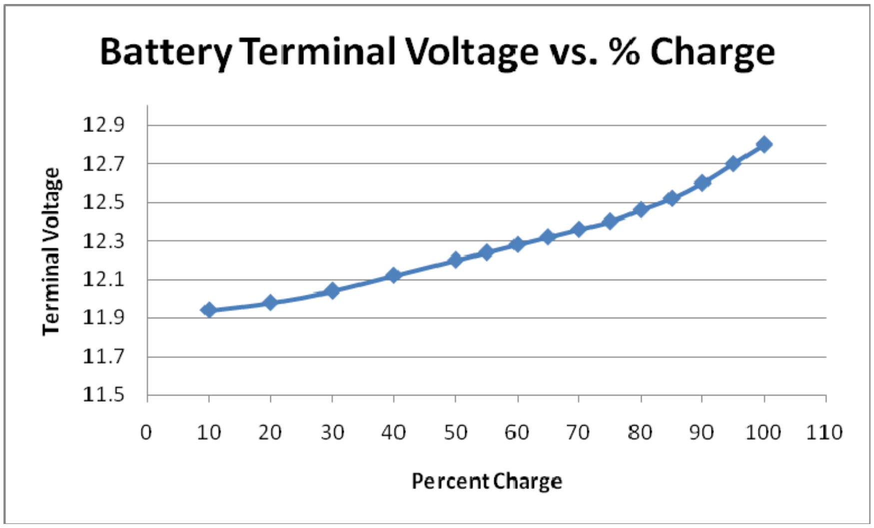

Figure 6: Battery Voltage vs. State of Charge [7]

Charge Controller:

Initially, a maximum power point tracking (MPPT) charge controller was planned for use in this project. MPPT charge controllers are generally switched mode DC-DC converters which vary the switching duty cycle to regulate the RMS output voltage to match the charging voltage of the battery, while maintaining the input voltage at the maximum power point on the panel's I-V characteristic curve. However, all MPPT controllers researched were priced in the range of $200-$400. Therefore, a less expensive solution had to be found.

Instead of using MPPT controller, the controller in this project was designed using two LM317 voltage regulators, a TLV2302IP dual comparator, two IRF510 power MOSFET chips, and a 9 V battery. The comparator detects when the battery is fully charged by comparing the terminal voltage to a regulated 14.5 V reference. When the battery terminal voltage exceeds 14.5 V, the comparator sends a low signal to the gate of a charging MOSFET between the battery and the solar panel, opening the circuit to prevent overcharging. Similarly, the comparator detects when the battery is at its lowest allowable state of charge by comparing its voltage to a regulated 12 V reference. When the battery terminals are at this minimum voltage, the comparator sends a low signal to the gate of a MOSFET connected between the battery terminals and the inverter, opening the circuit and disconnecting the load. See Figure 3 above to see the how the control circuit connects to the other subsystems. Although at full charge the terminal voltage is about 12.8 volts, the battery must charge to 14.5 V to overcome its charging resistance, caused by internal pressure within the charging battery cell.

Inverter:

The AIMS 400 W Modified Sine Wave Inverter was selected for its output voltage 120 V, 60 Hz AC and for its low retail price of $34. It has a nominal maximum output power of 400 W, so it can easily supply the 40 W load for this project. Additionally, it has shutoff features to protect from low or high DC input voltages and high AC currents. See Table 8, below, for the nominal minimum and maximum DC voltages and maximum AC current, as provided by the manufacturer.

	Low DC Voltage Limit	High DC Voltage Limit	High AC Current Limit
Nominal	10 V	16.5 V	3.33 A RMS

Table 8: Nominal Inverter Voltage and Current Limitations

Other Component Considerations:

Initially, a switched mode regulator was planned to regulate the input voltage to the inverter from the battery. This regulator would ensure that the actual input voltage to the inverter matches the nominal 12 V. However, the selected AIMS 400 W Inverter allows for an input voltage range from 16.5 V down to 10 V, outside of which, the inverter will turn itself off. Since the battery voltage control circuits will prevent the battery from exceeding 14.5 V or dropping below 12 V, the inverter will not receive any voltages outside of its input range, so a voltage regulator is not needed. Additionally, the low voltage turnoff feature of the inverter provides an extra measure of protection from excessive battery discharge.

A blocking diode is sometimes used for protection of the panels. If the panels are shadowed, they will stop producing voltage and become a load for the battery. The diode opens the circuit in the event of low panel voltage to prevent reverse current from damaging the panel. However, most PV arrays, including the BP SX 150S, have multiple protection and bypass diodes built in to each string of cells to ensure that if part of the panel is shaded, the shadowed strings will be disconnected by the diodes, while allowing the rest of the panel to continue producing power. Therefore, a blocking diode is not needed for this project.

IMPLEMENTATION AND TESTING

Panel:

The first measurement taken on the panel was its current versus voltage characteristic curve (I-V curve). The two different curves were measured on March 3 and March 12, 2011, and were taken using the BK Precision 8540 150 W DC Electronic Load. By determining the load current, the panel is constrained to operate at the corresponding voltage, determined by the I-V curve. The electronic load allowed this current to be specified and varied, and both current and voltage could be measured. See Figure 7, below, for the complete measured I-V characteristics of the panel.

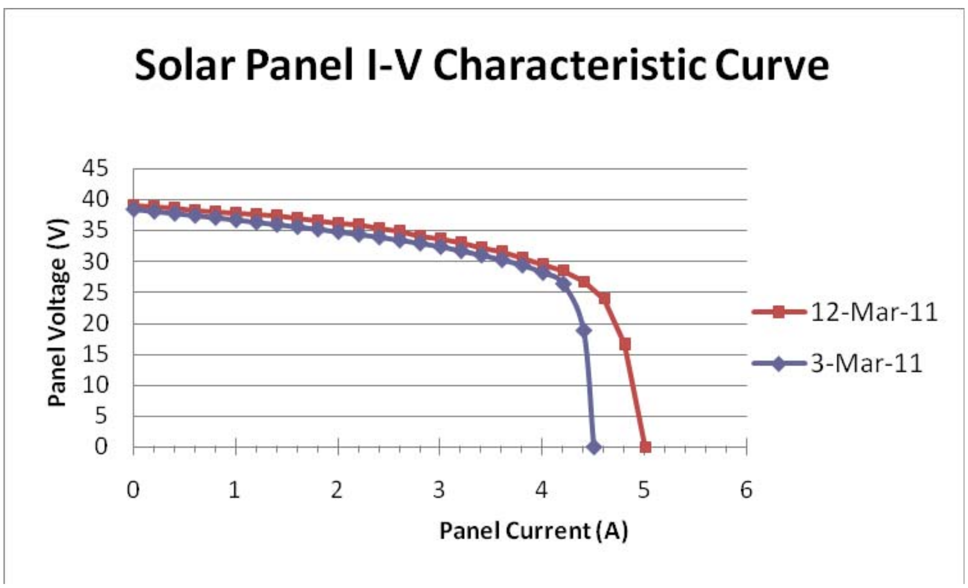

Figure 7: BP SX 150S Panel I-V Characteristic Curve

Given in Table 9 below are the nominal and measured characteristics for the BP SX 150S panel.

	Voc (V)	Isc (A)	Vmp (V)	Imp (A)	Pmax (W)	Fill Factor
Nominal	43.50	4.75	34.50	4.35	150.08	0.73
Measured	38.38	4.50	28.15	4.00	112.60	0.65

Table 9: Nominal and Measured Panel Characteristics

The variables named in the table above are defined as follows: Voc = Open Circuit Voltage, Isc = Short Circuit Current, Vmp = Max Power Voltage, Imp = Max Power Current, Pmax = Panel Maximum Power Output. The panel has a calculated fill factor of 0.65 based on the measured data, according to the equation:

Fill Factor = (Vmp*Imp) / (Voc*Isc)

The next test done on the panel was to determine the variance in open circuit voltage and short circuit current as the inclination of the panel was adjusted. This test was done on April 15. According to Table 7 above, the inclination to match the Sun's zenith angle on April 15 is 24.85 degrees South. The panel's inclination was varied from 0 degrees (horizontal) to 90 degrees (vertical, with the surface facing due South) in 5 degree increments, and the open circuit voltage and short circuit current were measured at every angle. This data was plotted in Figures 8 and 9, below.

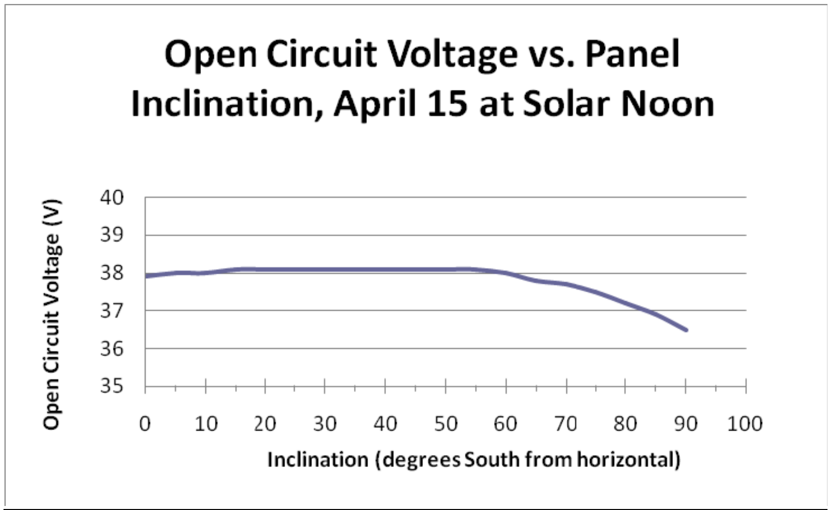

Figure 8: Solar Panel Open Circuit Voltage versus Inclination Angle, measured April 15 at Solar Noon

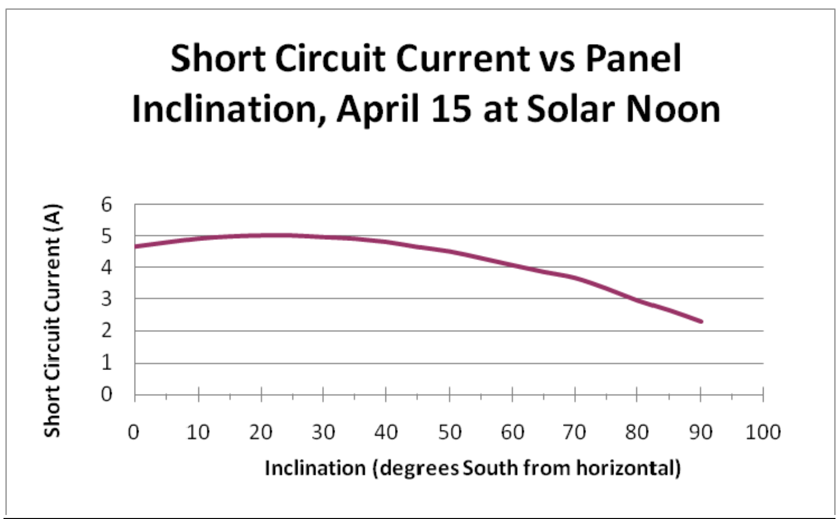

Figure 9: Solar Panel Short Circuit Current versus Inclination Angle, measured April 15 at Solar Noon

The peak values for these curves fall between 20 and 25 degrees South. This supports the value of 24.85 degrees South predicted in Table 7, above.

Battery:

The first test done on the Werker WKDC12-33PUS battery was to determine its actual voltage at full charge and at 20% capacity, the design discharge limit. The battery was first charged up to 14.5 V, as provided by the datasheet, to ensure that it was fully charged. When disconnected from the panel, the terminal voltage was measured to be 12.80 V. It was then discharged at the maximum design DC load current, 3.3 A, using the BK Precision 8540 150 W DC Electronic Load. The maximum load current gives the battery's minimum efficiency condition. After discharging the battery at this current for one half hour, a total of 1.65 Ah was discharged from the battery's capacity, which is one-twentieth of the total rated capacity. This was done in half-hour increments until 26.4 Ah had been discharged, 80% of the rated capacity, leaving 20% remaining. The terminal voltage was measured at each increment. The final terminal voltage was measured to be 11.96 V. This data is shown plotted against the manufacturer's stated voltage versus charge curve in Figure 10 below.

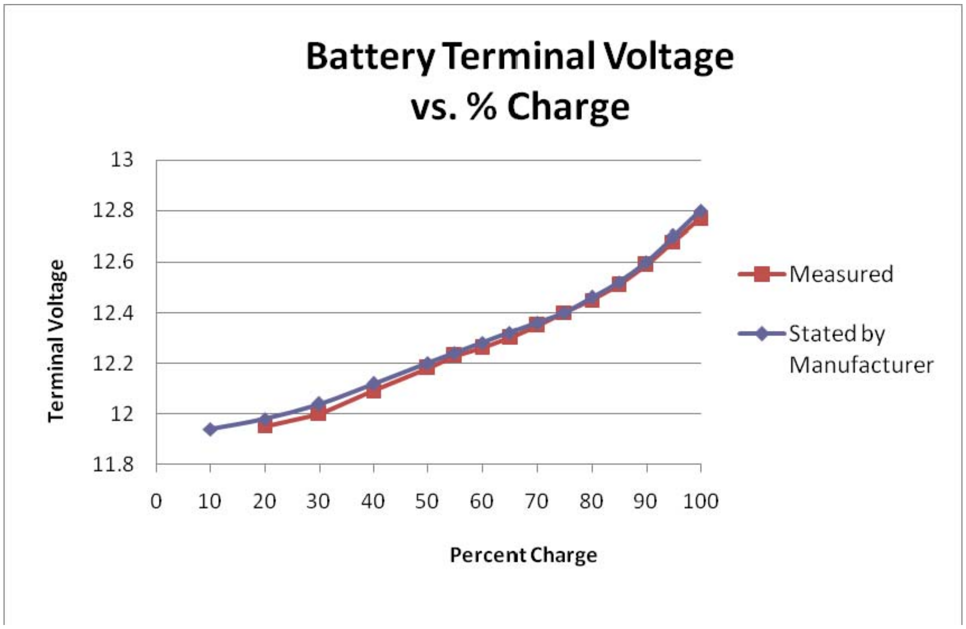

Figure 10: Nominal and Measured Battery Terminal Voltage versus State of Charge [7]

The battery's round trip efficiency was measured next, by calculating and plotting the power as it was discharged down to 20% capacity, and then measuring the current and voltage as it was charged back up to 100% capacity (when terminal voltage reaches 14.5 V). The battery was recharged by connecting it directly to the panel, allowing it to charge at about 4.4 A. Once this was done, the charging power was also calculated at each increment, by multiplying the charging current and the charging voltage together. Tables 10 and 11, below show the discharging and charging current, voltage, and power, measured every half hour, between 20% capacity and 100% capacity. For the plot of power versus time, see Figure 13 in the Analysis section, below.

Hours	Terminal Voltage (V)	Current (A)	Power (W)
0	12.77	3.3	42.141
0.5	12.69	3.3	41.877
1	12.61	3.3	41.613
1.5	12.54	3.3	41.382
2	12.47	3.3	41.151
2.5	12.41	3.3	40.953
3	12.36	3.3	40.788
3.5	12.31	3.3	40.623
4	12.27	3.3	40.491
4.5	12.23	3.3	40.359
5	12.19	3.3	40.227
5.5	12.15	3.3	40.095
6	12.11	3.3	39.963
6.5	12.08	3.3	39.864
7	12.04	3.3	39.732
7.5	12	3.3	39.6
8	11.96	3.3	39.468

Table 10: Discharging Battery Voltage, Current, and Power measured against Time

Hours	Terminal Voltage (V)	Current (A)	Power (W)
0	13.67	4.43	60.5581
0.5	13.72	4.43	60.7796
1	13.79	4.43	61.0897
1.5	13.86	4.43	61.3998
2	13.94	4.43	61.7542
2.5	14.02	4.42	61.9684
3	14.1	4.42	62.322
3.5	14.17	4.42	62.6314
4	14.23	4.42	62.8966
4.5	14.29	4.42	63.1618
5	14.35	4.42	63.427
5.5	14.4	4.42	63.648
6	14.44	4.41	63.6804
6.5	14.49	4.41	63.9009

Table 11: Charging Battery Voltage, Current, and Power measured against Time

Charge Controller:

One problem encountered when implementing this control circuit was that that the regulated outputs needed from the LM317 linear regulators were either above the battery voltage or less than 1.5 volts below it. Therefore, to ensure that the input voltage to the regulators was high enough above the desired output, a 9 V battery was connected in series with the 12 V battery to supply a nominal input voltage of 21 V to the LM317 chips (see Figure 3). This ensured that the regulated reference voltages would remain constant and accurate while allowing for any necessary internal voltage drops within the regulators.

The 12 V regulator uses an R1 value of 240 Ohms and an R2 value of 2047 Ohms, which gives a nominal regulated output voltage of 12.01 V, according to the equation

$$\mathbf{Vreg = 1.25*(1+R2/R1) + Iadj*R2}$$

obtained from the LM317 datasheet, where Iadj = ~50uA. The actual measured output voltage of this regulator is 11.97 V.

The 14.5 V regulator uses an R1 value of 240 Ohms and an R2 value of 2530 Ohms, which gives a nominal regulated output voltage of 14.55. The actual measured output voltage of this regulator is 14.41 V. See Table 12 for a summary of the LM317 resistor and voltage values.

	R1 (Ohms)	R2 (Ohms)	Vnominal (V)	Vmeasured (V)
12 V Regulator	240	2047	12.01	11.97
14.5 V Regulator	240	2530	14.55	14.41

Table 12: LM317 Voltage Regulator Resistor Values

and Nominal and Measured Regulated Voltages

IRF510 MOSFET transistors are used as switches in this project to connect the battery to the panel and to the inverter. These MOSFETs are rated for up to 4 Amps, and a 12 V nominal gate-source voltage is used to turn them on. This gate-source voltage is supplied by the TLV2302IP comparator (see Figure 3, above). The actual output voltage of this comparator is its supply voltage (taken from the battery), plus or minus .3 V, according to the datasheet, meaning that the gate-source voltage should be within 0.3 V of the battery voltage.

The first measurement taken on the MOSFETs was the gate-source voltage with respect to battery voltage. By design, the load MOSFET (connecting the battery to the inverter) should turn off below 12 V, while the panel MOSFET (connecting the battery to the solar panel) should turn off above 14.5 V. The data shown in Figure 11 verifies that this is the case.

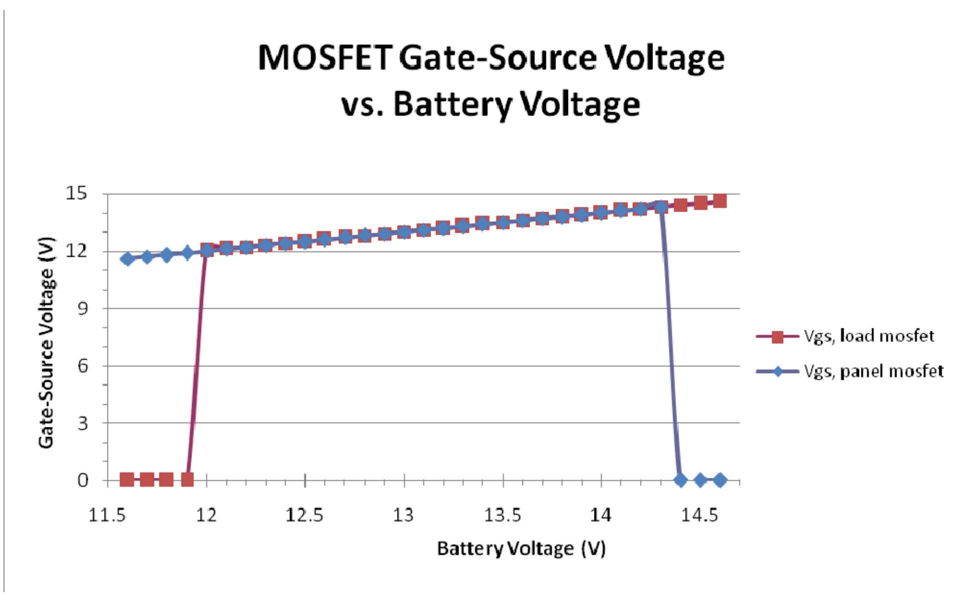

Figure 11: MOSFET Gate-Source Voltages

versus Battery Voltage

Inverter:

The first testing done on the inverter was the verification of the automatic shut off limits. If the input voltage or output current strays outside of these limitations, an alarm will sound, and the inverter will enter automatic shut off mode until the violating conditions are cleared. Table 13 below details the manufacturer's stated limitations and those measured in lab.

	Low DC Voltage Limit	High DC Voltage Limit	High AC Current Limit
Nominal	10 V	16.5 V	3.333 A RMS
Measured	10.12 V	16.35 V	3.309 A RMS

Table 13: Nominal and Measured

Inverter Voltage and Current Limitations

Next, the efficiency of the inverter had to be measured. This measurement was done between no-load and full load conditions by varying the AC load in (approximately) 4 W increments. Note that full load conditions for this project mean an AC load of 40 W, even though the inverter can support up to a 400 W load.

To take these measurements, 4 W cell phone chargers and 12 W CFL bulbs were added to a power strip plugged into the inverter. The two wires of the power strip were split apart and one was connected through an ammeter. The AC voltage was measured with a voltage meter connected between the two wires. Both the DC current and the DC voltage were also measured at the inverter's input. Table 14 shows the data collected by varying the load from 0 to 40 W. Figure 17, in the "Analysis" section below, shows the efficiency curve plotted over this range.

Vdc (V)	Vac,rms (V)	Idc (A)	Iac,rms (A)	Pdc (W)	Pac (W)	Efficiency
12.6	120.86	0.07	0	0.88	0.00	0.00
12.6	120.83	0.46	0.033	5.80	3.99	0.69
12.6	120.72	0.82	0.068	10.33	8.21	0.79
12.6	120.75	1.18	0.102	14.87	12.32	0.83
12.6	120.68	1.51	0.135	19.03	16.29	0.86
12.6	120.69	1.86	0.169	23.44	20.40	0.87
12.6	120.62	2.24	0.207	28.22	24.97	0.88
12.6	120.57	2.55	0.24	32.13	28.94	0.90
12.6	120.59	2.85	0.273	35.91	32.92	0.92
12.6	120.54	3.18	0.306	40.07	36.89	0.92
12.6	120.5	3.46	0.335	43.60	40.37	0.93

Table 14: Inverter Voltage, Current, Power and Efficiency Measurements

ANALYSIS

Panel:

As may be seen in Figure 7, above, the 12 to 14.5 V operating voltage of the panel is well below the maximum power point voltage of 28.15 V (Table 9, above). Fortunately, the panel is sized large enough that it can still produce sufficient power, while operating below the maximum power point voltage. According to the project requirements discussed above, the panel must produce at least 190 Wh per day. This can be accomplished by generating 38 W for 5 hours a day. Operating at the minimum battery voltage of 12 V and producing 4.4 A, this still gives a 52.8 W power output. According to the equation

$$\mathbf{E_{panel} = P_{panel} * Time}$$

the panel will replenish the daily energy used by the load in 3.6 hours of full sunlight.

The predicted panel inclination angles in the month of March (Table 7) were supported by the data collected and shown in Figures 8 and 9. One interesting point of note is that the current varied widely with respect to angle, whereas the voltage varied only slightly. The open circuit voltage versus inclination angle curve varies by less than 2 V. The short circuit current, however, varies from 2 to 5 A over the range tested, and would continue to drop to zero as the panel surface becomes parallel with the incident light. In fact, the relationship between open circuit current and panel inclination is sinusoidal, as shown in Figure 12 below. The open circuit current is plotted over a sine wave to show the similarity. The peak of the plotted sine wave is centered at 25 degrees, which corresponds to the predicted maximum current angle.

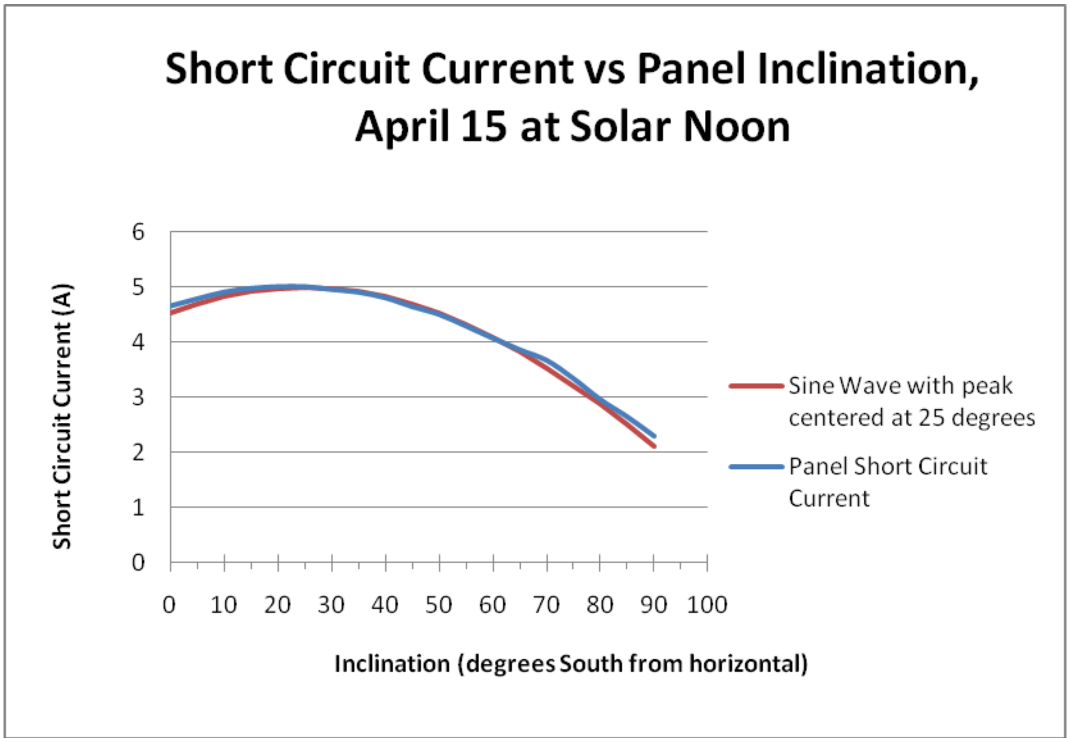

Figure 12: Short Circuit Current versus Panel Inclination plotted against 25 Degree-Shifted Sine Wave

Battery:

The battery round trip efficiency can be calculated by plotting the charging and discharging power versus time (Figure 13, below). By estimating the area under each graph (which gives energy in Wh), the total charging and discharging energy values may be found. Note that the battery voltage recharged to 14.5 V in less time than it took to discharge to 12 V. The discharging power varied around 41 W, and it took 8 hours to discharge to 12 V.

(41 W) * (8 hours) = **(328 Wh)**

The charging power varied around 62 W, and the battery charged up to 14.5 V in 6 hours.

(62 W) * (6.5 hours) = **(403 Wh)**

The round trip efficiency is calculated as follows:

Efficiency = E(out) / E(in) = 328/403 = **81.39%**

Though these are only approximations, this experiment shows that the battery efficiency is very close to the requirement of an 80% round trip efficiency.

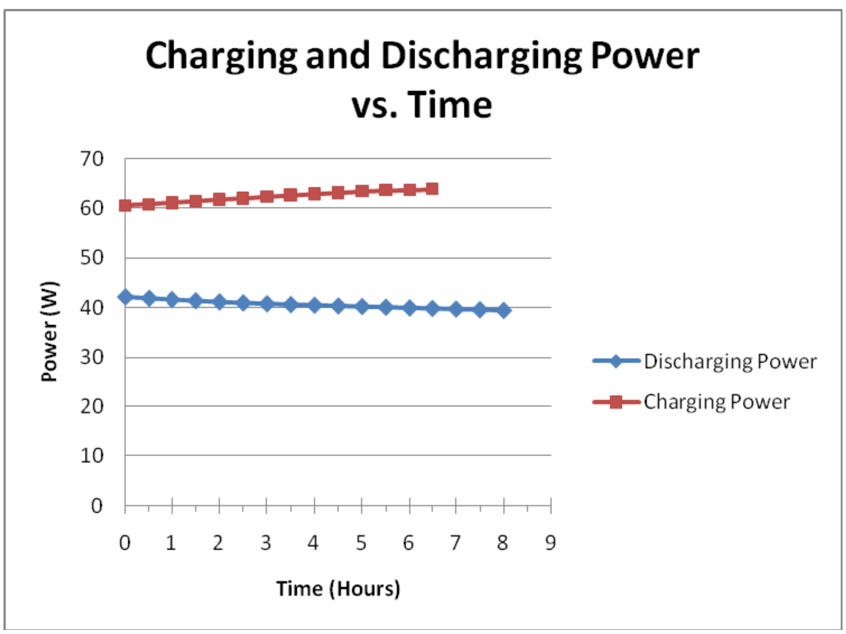

Figure 13: Charging and Discharging Power versus Time

Charge Controller:

The plots in Figures 14 and 15 show the drain-source resistance and power dissipation at various load currents. This shows that power dissipation in the MOSFETs in non-negligible at high currents. The maximum drain-source current that would occur in this project is 3.3 A. Under this full load condition, the MOSFET dissipates almost 4 W. The load power at this value is 40 W, meaning at full load, the MOSFET control circuit efficiency is only 90%. This inefficiency was unaccounted for in the initial sizing calculations, and it adversely affects the battery life.

Fortunately, the selection of a 33 Ah battery, which gives 18 Wh above the required 31.5 Ah battery capacity, can make up for this MOSFET inefficiency. The project is designed for less than 4 hours a day at full load. The MOSFET loss of 4 W for 4 hours comes to 16 Wh lost to the MOSFET, so the extra 18 Wh in the battery capacity can cover this if necessary.

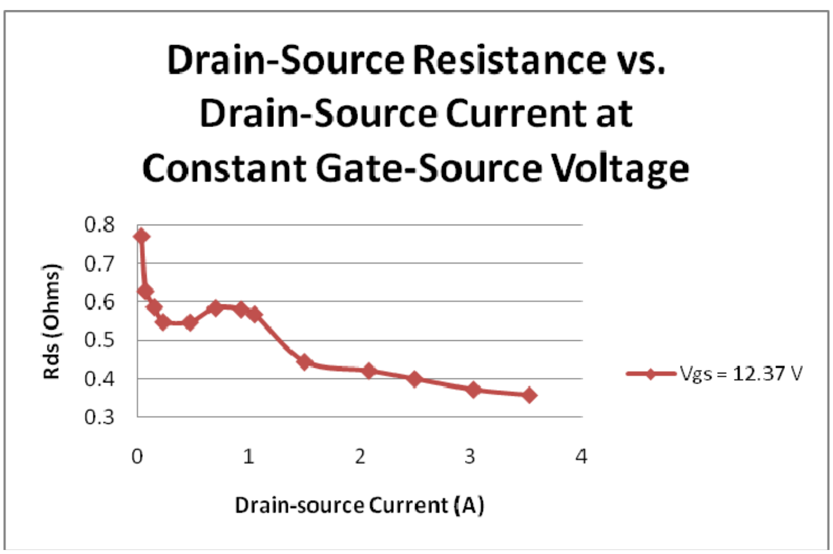

Figure 14: Drain-Source Resistance versus Drain-Source Current with Gate-Source Voltage held constant

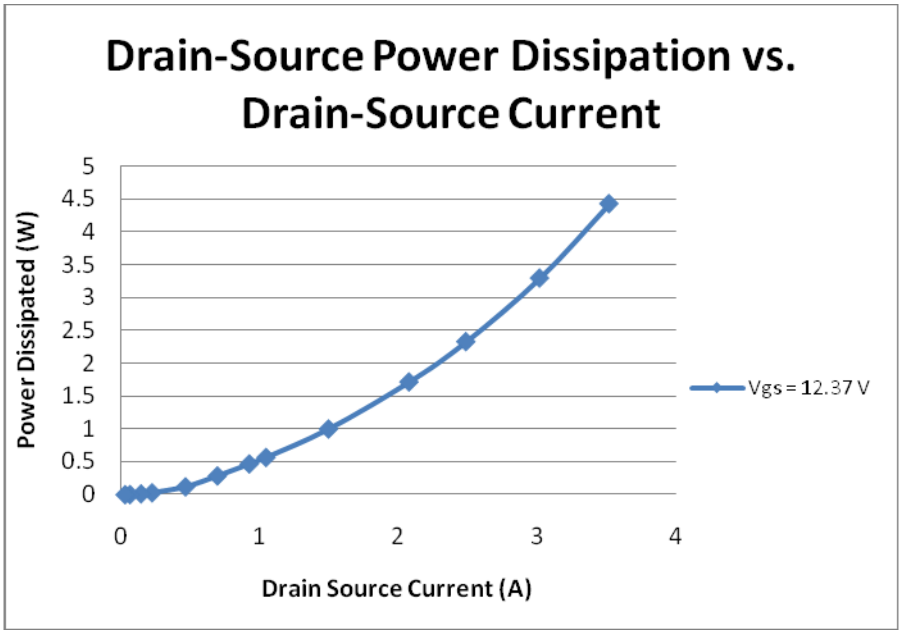

Figure 15: Drain-Source Power Dissipation versus Current

with Gate-Source Voltage held constant

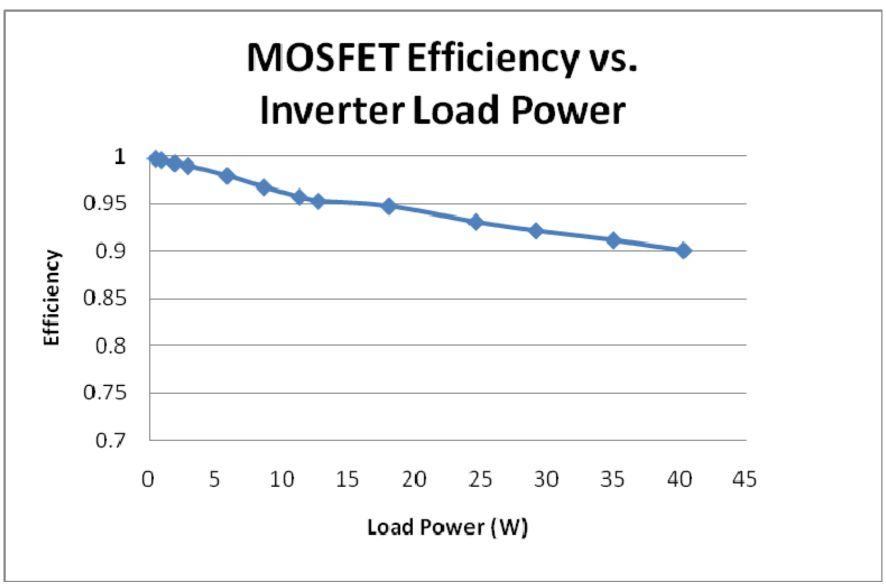

Figure 16: Discharging MOSFET Efficiency versus

Inverter Load Power

A disadvantage of using this control circuit rather than a MPPT charge controller is that the panel is forced to operate at the battery voltage, which is well below the maximum power voltage on its I-V characteristic curve. If operated at the panel's maximum power point, the power output would be (28.15 V)*(4 A) = (112.6 W). Operated at the battery voltage, the maximum possible power output is (14.5 V)*(4.4 A) = (63.8 W). If this project were to be manufactured for commercial or humanitarian purposes, a MPPT controller would be recommended to improve the panel output power to its full potential.

Inverter:

<u>Efficiency:</u>

For the inverter to operate above a 90% efficiency, it must be supplying an AC load of no less than 29 W (see Figure 17 below). Below this value, the inverter consumes more than 10% of the total power it draws. In addition to resistive losses, this power is used to run the fan to cool the internal electronics. This inefficiency at low loads could be problematic for the project, because if power use is distributed throughout the day, the efficiency may never rise above 90%. This could happen if the appliances are all used one or two at a time, rather than altogether. This is a very plausible scenario.

The panel for this project can produce up to 64 W when operated at 14.5 V **(Figure 7, above)**, and the minimum required power output is 38 W. This means when the Sun is shining, the panel will produce more than enough power to power the load while keeping the battery fully charged, regardless of the inverter's inefficiency. The only circumstance which might overdraw the battery would be a period of extended use with little or no sunlight. In such cases, it may be necessary to either decrease daily energy use, or else consolidate usage times so that the load power remains above 29 W.

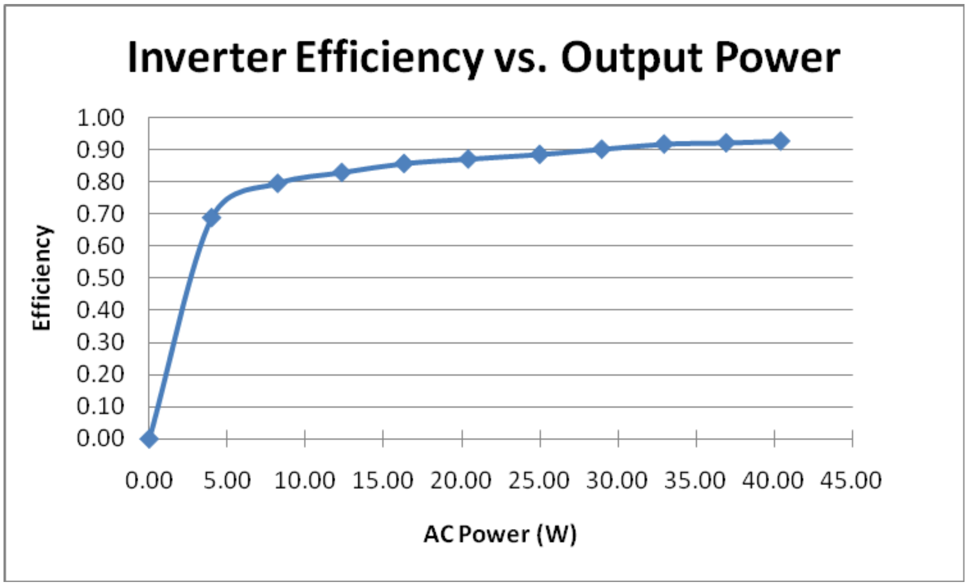

Figure 17: Inverter Efficiency versus Load Power

from No Load to 40 W Load Conditions

Harmonic Content:

Figure 18, below, shows the output waveform for the AIMS 400 W Modified Sine Wave Inverter. This "stepped" square wave is preferable over a true square wave, because in a square wave, harmonics occur on every odd numbered multiple of the fundamental frequency. By using a delay angle of 30 degrees, all of the triplet harmonics are suppressed, allowing for easier filtering of the fifth and higher non-triplet harmonics. A 30 degree delay angle means that the positive cycle will occur between 30 and 150 degrees, and the negative cycle between 210 and 330 degrees. In general, the nth harmonic and its multiples are suppressed if the delay angle is (90 degrees)/n.

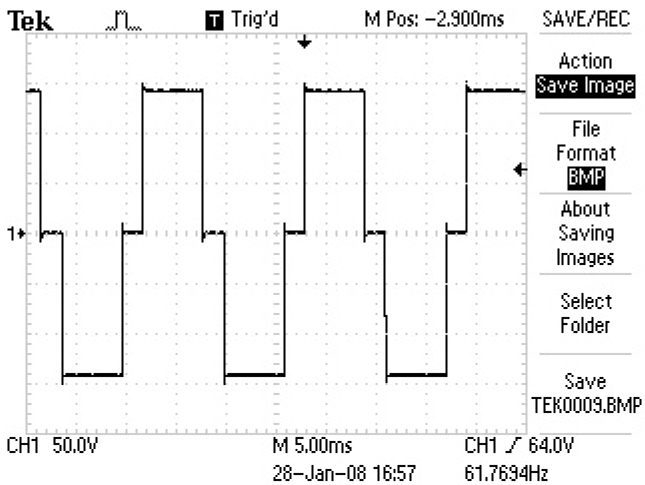

Figure 18: AIMS 400 W Modified Sine Wave Inverter Voltage Waveform [6]

OPPORTUNITIES FOR FURTHER DEVELOPMENT AND STUDY

One area that would benefit from further testing is the open circuit voltage and short circuit current plots, with respect to panel inclination. These plots were only taken for one month of the year. While the data collected matches the predicted data almost perfectly, it would be beneficial to make similar measurements during other months of the year and verify that the other predicted inclination angles (Table 7) are also correct.

The construction of some type of tilt frame would be helpful to this end. If the panel were allowed to pivot up and down about its east-west axis, the collection of this inclination data would be greatly facilitated. This frame could include a locking mechanism that would hold the panel in place once adjusted to the proper angle.

Another opportunity for further testing is the battery capacity with variances in temperature. While the system should work as tested in San Luis Obispo, where the temperature seldom drops to freezing, even in the winter time, the capacity may be adversely affected by extremes of cold or hot temperatures. Such temperature related data would be helpful in adapting this project to locations in different climates.

An improvement on the implementation could be made by replacing the breadboard with a printed circuit board, to which the components could be soldered. While there were no problems inherent in the use of the breadboard, a soldered PCB would give the project a more finished look.

An improvement that would enhance the functionality of this project would be the replacement of the selected MOSFETs with similar devices rated for larger drain-source currents. The MOSFETs used in this project were rated for 4 A, and they were the main limiting factor in instantaneous power drawn. The inverter can support up to 400 W, which amounts to 3.3 A on the 120 V AC side. However on the 12 V DC input, this would amount to 33.3 A. Hypothetically, the system would benefit from MOSFET ratings increased up to this 33.3 A value. However, under these conditions the battery capacity would need to be increased substantially as well to support such a load for any sustained length of time.

Another improvement that would increase the functionality of the project would be the implementation of a maximum power point tracking (MPPT) charge controller. This would replace the charge control circuit discussed in this project. Initially, a MPPT charge controller was to be used, but the $200-400 price tag exceeded the budget limitations for this component. MPPT charge controllers are generally buck or buck-boost switched-mode converters, which allow the panel to operate at its maximum power point on the I-V characteristic curve. Using power electronics, the panel voltage is stepped down to the level of the battery charging voltage, and the current is stepped up proportionally, allowing the battery to maximize the power it receives from the panel. If used in this project, the panel could consistently operate at 28.2 V and 4 A, which would give about 113 W, as opposed to the maximum of 64 W (14.5 V, 4.4 A) under the current configuration.

An even more ambitious addition to this project would be the design and implementation of a solar tracking system, which would detect the Sun's hour angle and adjust the panel to the east or west throughout the day. This could be implemented using photo diodes placed on either side of the panel, and a comparator to detect the difference in light received between the two. The comparator would need to have +/- rails, rather the TLV2302 comparators used in the control circuit discussed above, which use +/GND type rails. The comparator could then output a positive or negative signal to a DC motor, which would rotate the panel to correct any inequalities in insolation between the two photodiodes.

CONCLUSION

After experimental data was collected, the system was determined to operate within stated requirements with the exception of inverter efficiency at low load values. The inverter AC voltage varied between 120 and 121 V RMS between no-load and full load. Its allowable DC voltage range between 10.12 and 16.35 V easily accommodated the battery voltage of 12 to 14.5 V, and the 400 W load rating far exceeded the requirement of 40 W AC. The only problem with the inverter was inefficiency at loads below 29 W, smoothly varying down to zero at no-load conditions. Above 29 W the efficiency met the requirement of 90%.

The panel produces 52 to 64 W at the battery voltage of 12 to 14.5 V on sunny days, which is sufficient to keep the battery charged while in use. By adjusting the panel inclination angle monthly, according to the angles given, this power output can be maintained throughout the year.

The control circuit accurately detects when the battery is outside of the 12 V to 14.5 V window and effectively prevents further discharging or charging by disconnecting it from the inverter or the panel, respectively. The efficiency was observed to drop to 90% as the DC current approached its full load value, which may decrease battery life during periods of heavy use without sunlight.

The battery has a 33 Ah capacity, which provides 1.5 extra Ah above the minimum requirement. This extra capacity can help to mitigate inefficiency losses of the control circuit at high loads or the inverter at low loads. The battery round trip efficiency at full load was measured to be 81.39%, meeting the requirement of 80% minimum battery efficiency.

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8. IRF 510 datasheet, Fairchild Semiconductor
9. TLV2302IP datasheet, Texas Instruments
10. LM317 datasheet, Texas Instruments
11. Photovoltaic System Sizing Worksheet, provided by Dr. Samuel Agbo

APPENDIX A:

SYSTEM SPECIFICATIONS

Panel:

- Operates up to at least 15 V
- Power output of at least 38 W at this voltage level

Battery:

- 31.5 Amp-hour capacity
- Allowable depth-of-discharge down to 20% capacity
- At least 80% round trip efficiency

Charge Control Circuit:

- Detects when battery voltage falls below 12 V
    - Disconnects battery from load (inverter)
- Detects when battery voltage exceeds 14.5 V
    - Disconnects battery from panel

Inverter:

- 60 Hz, 120 V RMS output voltage
- 12 V DC input voltage
- Rated for at least 40 W
- 90% efficiency

APPENDIX B:

PARTS LIST AND COST

Component	**Cost**	**Notes**
Panel	$0.00	Borrowed from EE Dept.
Werker WKDC12-33PUS 12 V Battery	$106.91	Purchased from BatteriesPlus
Duracell 9 V Battery	$4.99	Purchased from BatteriesPlus
IRF510 n-channel MOSFET x2	$3.98	Purchased from Radioshack
TO-220 Heat Sink x2	$4.98	Purchased from Radioshack
LM317 Voltage Regulators x2	$3.98	Purchased from Radioshack
TLV2302IP Dual Comparator	$0.00	Free sample from Texas Instruments
AIMS 400 W Inverter	$51.72	Purchased from TheInverterStore.com
Assorted Resistors and Wiring	$5.00	
Total Cost	**$181.56**	

Table 15: Component Costs

APPENDIX C:

Sizing of Stand-Alone Photovoltaic Systems WORKSHEET

Application Off - Grid Photovoltaic Design Project

Location San Luis Obispo, CA **Latitude** 35 ° N

A. Loads

A1	Inverter efficiency (decimal)	0.9	
A2	Battery bus voltage	12	volts
A3	Inverter ac voltage	120	volts

Component	A4 Rated Wattage	A5 Adjustment Factor 1.0 for dc (A1) for ac	A6 Adjusted Wattage (A4/A5)	A7 Hours Per Day Used	A8 Energy Per Day (A6 x A7)
LED Light Bulb	12W	.9	13.3	5	66.5
LED Light Bulb	12W	.9	13.3	5	66.5
Cell Phone Charger	4 W	.9	4.44	1	4.44
Cell Phone Charger	4 W	.9	4.44	1	4.44
Cell Phone Charger	4 W	.9	4.44	1	4.44
Cell Phone Charger	4 W	.9	4.44	1	4.44

A9	Total energy demand per day (summation of A8)	151	watt-hours
A10	Total amp-hour demand per day (A9/A2)	12.6	amp-hours
A11	Peak ac power requirement (summation of A4)	40	watts
A12	Peak dc power requirement (summation of A6)	44.4	watts

B. Battery Sizing

Design Temperature ______

B1	Days of storage desired/required	2	days
B2	Allowable depth-of-discharge limit (decimal)	0.8	
B3	Required battery capacity (A10 x B1/B2)	31.5	amp-hours
B4	Amp-hour capacity of selected battery *	33	amp-hours
B5	Number of batteries in parallel (B3/B4) (round up)	1	
B6	Number of batteries in series (A2/battery voltage)	1	
B7	Total number of batteries (B5 x B6)	1	
B8	Total battery amp-hour capacity (B5 x B4)	33	amp-hours
B9	Total battery kilowatt-hour capacity (B8 x A2/1000)	.396	kilowatt-hours
B10	Average daily depth of discharge (.75 x A10/B8)	.2862	

* *Use amp-hour capacity at a rate of discharge corresponding to the total storage period, B1.*

A-2

C. Photovoltaic Array Sizing   Design Tilt 58.4°S   Design Month December

C1	Total energy demand per day (A9)	151	watt-hours
C2	Battery round-trip efficiency (0.70 - 0.85)	0.8	
C3	Required array output per day (C1/C2)	188.75	watt-hours
C4	Selected PV module max power voltage at STC x 0.85	34.5	volts
C5	Selected PV module guaranteed power output at STC (12V)*(5 peak sun hrs)=60	60	watts
C6	Peak sun hours at design tilt for design month	5	hours
C7	Energy output per module per day (C5 x C6)	300	watt-hours
C8	Module energy output at operating temperature. Use derating factor, DF = 0.80 for hot climates and critical applications; DF = 0.90 for moderate climates and non-critical applications (DF x C7)	270	watt-hours
C9	Number of modules required to meet energy requirements (C3/C8)	1	modules
C10	Number of modules required per string (A2/C4) rounded to next higher integer	1	modules
C11	Number of strings in parallel (C9/C10) rounded to next higher integer	1	strings
C12	Number of modules to be purchased (C10 x C11)	1	modules
C13	Nominal rated PV module output	52	watts
C14	Nominal rated array output (C13 x C12)	52	watts

D. Balance-of-System (BOS) Requirements

1. A voltage regulator is recommended unless array output current (at 1000 W/m^2 condition), less any continuous load current, is less than 5% of the selected battery bank capacity (at the 8-hour discharge rate).
2. Wiring should be adequate to ensure that losses are less than 1% of the energy produced.
3. In low voltage (i.e., less than 50 volts) systems, germanium or Schottky blocking diodes are preferred over silicon diodes.
4. Fuses, fuse holders, switches, and other components should be selected to satisfy both voltage and current requirements.
5. All battery series branches should contain fuses.
6. Fused disconnects are strongly recommended to isolate the battery bank from the rest of the system.